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Acoustically Coupled Ground Motion Under Controlled Conditions

Trial Study

Lindamae Peck

April 1992

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U.S. Army Corps
of Engineers
Cold Regions Research &
Engineering Laboratory

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Dr. Lindamae Peck, Geophysicist with the Geophysical Science Branch, Research Division, of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). This project was funded by Project No. 4A161102AT240F, *Winter Battlefield Sensor Systems*, Work Unit F15, *Computational Methods for Seismic Wave Propagation in Cold Regions*.

Stephen Decato was the human behind the pistol and the sledge hammer, and he moved a wall and a roof, which seemed like heaven and earth at times. Frank Perron and Thomas Tantillo designed the test basin roof and wall, which Ronald Farr built. Stephen Pugh, Paul Schwarz, and David Angier accommodated the acoustic coupling experiments in the FERF by minimizing equipment noise during the test periods. Paul Sellmann and Dr. Donald Albert of CRREL and Dr. James Sabatier of the National Center for Physical Acoustics at The University of Mississippi provided helpful comments on earlier versions of this report.

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LINDAMAE PECK

INTRODUCTION

Experimental studies of ground motion induced by low-frequency acoustic sources customarily are field investigations in which ground motion is measured at ranges of tens to hundreds of meters. It is impractical to intentionally vary the wet–dry or frozen–unfrozen state of the ground in a test area of several hundred square meters. If ground-motion experiments done on a smaller scale were found to provide useful results, then the dependence of acoustically coupled ground motion on such factors as the moisture content or the frozen–thawed state of the ground could be investigated systematically. The feasibility of doing ground motion studies under controlled conditions in the Frost Effects Research Facility (FERF) was determined with a series of studies in 1985 and 1986.

TEST FACILITY

One portion of the interior of the FERF is divided into eight rectangular test basins. The southwest test basin was selected for this study. Instead of a concrete floor, the base of this chamber is the local, fine-grained soil that was left in place during construction of the FERF.

A major consideration was to determine if acoustically coupled ground motion would be distinguishable from ground motion inherent to the FERF. Vehicle traffic around the FERF, particularly heavy equipment such as dump trucks and excavators, induces ground motion that propagates into the FERF. Mechanical activity, such as the action of pumps and air compressors, imparts vibrations to the FERF structure that couple into the ground. Some of the extraneous ground motion was reduced to a minimum with the assistance of the refrigeration staff, who shut down nonessential equipment during the acoustic-coupling experiments. Other equipment, however, operated automatically; therefore it was always possible that equipment could activate during the experiments.

A series of trial experiments was done to determine the characteristics of the ground motion inherent to the FERF. In March 1985, geophones, which are motion transducers that produce a voltage proportional to the velocity of ground motion, were placed at the surface of the soil in the southwest test basin. A time series record of the output of each geophone was obtained while various FERF mechanical equipment, such as pumps and air handlers, were in operation. The ground motion was of low amplitude and low frequency. It was recognizably different in amplitude and frequency content from the initial ground motion produced by the passage of the sound pulse used in field experiments of acoustically coupled ground motion. It would be more difficult to distinguish the FERF ground motion from the low-amplitude ground motion that follows the spike of ground motion induced by the passage of the sound pulse.

A second concern was how to freeze the soil in the test basin. The conventional means of freezing the contents of a test basin, which is to circulate supercooled brine through panels resting on the surface of the material in the test basin, could not be used because geophones and support stands for microphones would extend above the soil surface. A special method of indirectly using the brine to cool the southwest test basin was designed for this project. Instead of cooling panels in direct contact with the soil, a refrigeration unit was mounted at the top of the test basin; the air in that portion of the test basin was cooled by contact with the brine

pipes of the refrigeration unit, and the frigid air was then circulated by two fans. For this method to be effective, it was necessary that the test basin be enclosed to confine the cold air, yet it was desirable to have the test basin open during the ground motion experiments. The compromise was to have a movable roof and south wall that were in place during cooling periods and removed during ground-motion experiments. The wall and roof are described in the appendix.

The cold air method proved to be effective in freezing the soil because of the very low temperature (−30°C) of the circulating air. The corresponding method of thawing the soil, exposing it to the relatively warm air of the FERF, was much less effective because the temperature of the FERF air was approximately that of the outside air. Warming the soil by exposing it to the air in the FERF would be much more successful during summer months than it was in February and March 1986 during the acoustic-coupling experiments.

The final consideration was whether the reverberation of sound in the test basin would be detrimental to the ground motion experiments. In the field, acoustic experiments are normally done in open areas so that reflected-sound arrivals are limited to sound reflected at the ground surface. In the FERF, sound is reflected at the three walls (east, north, west) of the test basin as well as at the soil surface. In addition, multiply reflected sound (sound reflected at more than one surface) may be strong enough to induce ground motion. Time series records from microphones showed that sound reverberation was pronounced but that it was negligible after 1 second. Provided that the time offset between the passage of the direct sound wave and the arrival of primary reflected sound (sound reflected once, at one of the walls) could be resolved on the time series record of ground motion, the occurrence of reverberation was not a problem.

After the preliminary study of ground motion inherent to the FERF was completed, the test basin was filled with sand to a depth of 70 cm. The surface of the sand was level with the edge of the ramp that extended up from the south boundary of the test basin to the floor level of the FERF. The sand covered the in situ soil and the concrete footings at the base of the walls. The commercially purchased sand was classified as well graded, clean sand with a moisture content of 2–3%. Ten determinations of compressional wave speed in the sand over a range of 5 m (0.5-m increments) gave values ranging from 210 to 280 m/s. These values were obtained from a linear regression of the time to onset of ground motion vs geophone-source separation. Before the sand was placed in the test basin, a similar determination of compressional wave speed in the in situ soil had resulted in values of 250–310 m/s.

INSTRUMENTATION

Ground motion was measured with geophones grouped in clusters of 3 or 4 that were in 7 locations in the test basin (Fig. 1). The clusters of 3 were low-frequency (4.5-Hz) geophones at locations A, B, C, D, and F. The geophones were at the sand surface and at depths of 12 and 20 cm. Clusters B, D, and F were vertical-orientation geophones that produced voltage proportional to the vertical component of the velocity of ground motion. Clusters A and C were sensitive to horizontal ground motion in the north–south and east–west directions, respectively. Clusters E and G were high-frequency (14-Hz) vertical-orientation geophones; each cluster had a geophone at the sand surface and at depths of 15, 30, and 45 cm. Four additional low-frequency geophones (G1–G4) at the sand surface, together with surface geophone D, formed a linear array of 4 m extent.

The geophones were spaced about the test basin so that ground motion induced by sound reflected at the basin walls could be identified by the relative offset in time among arrivals at the different locations. It was also expected that any location-dependent nonuniformity in cooling and warming the sand would be evident; this information would assist in designing a planned follow-on set of experiments.

Low-frequency capacitance microphones were located at positions M1–M8 (Fig. 1). They were either at the sand surface or on support platforms at a height of 0.85 cm. The microphones have a flat frequency response (to within 3 dB) over the frequency range 0–500 Hz. They were covered with wind screens during the ground motion experiments to duplicate the standard field set-up.

The output voltage of the geophones and microphones was digitized and written to 9-track magnetic tape by a 24-channel seismic recording system. Each sensor's output was low-pass filtered at 500 Hz and sampled at a frequency of 2 kHz. Six data files were recorded for each test condition; of these, three files were different combinations of the sensors and three files were repeat experiments. A particular sensor was represented in four of each set of six files.

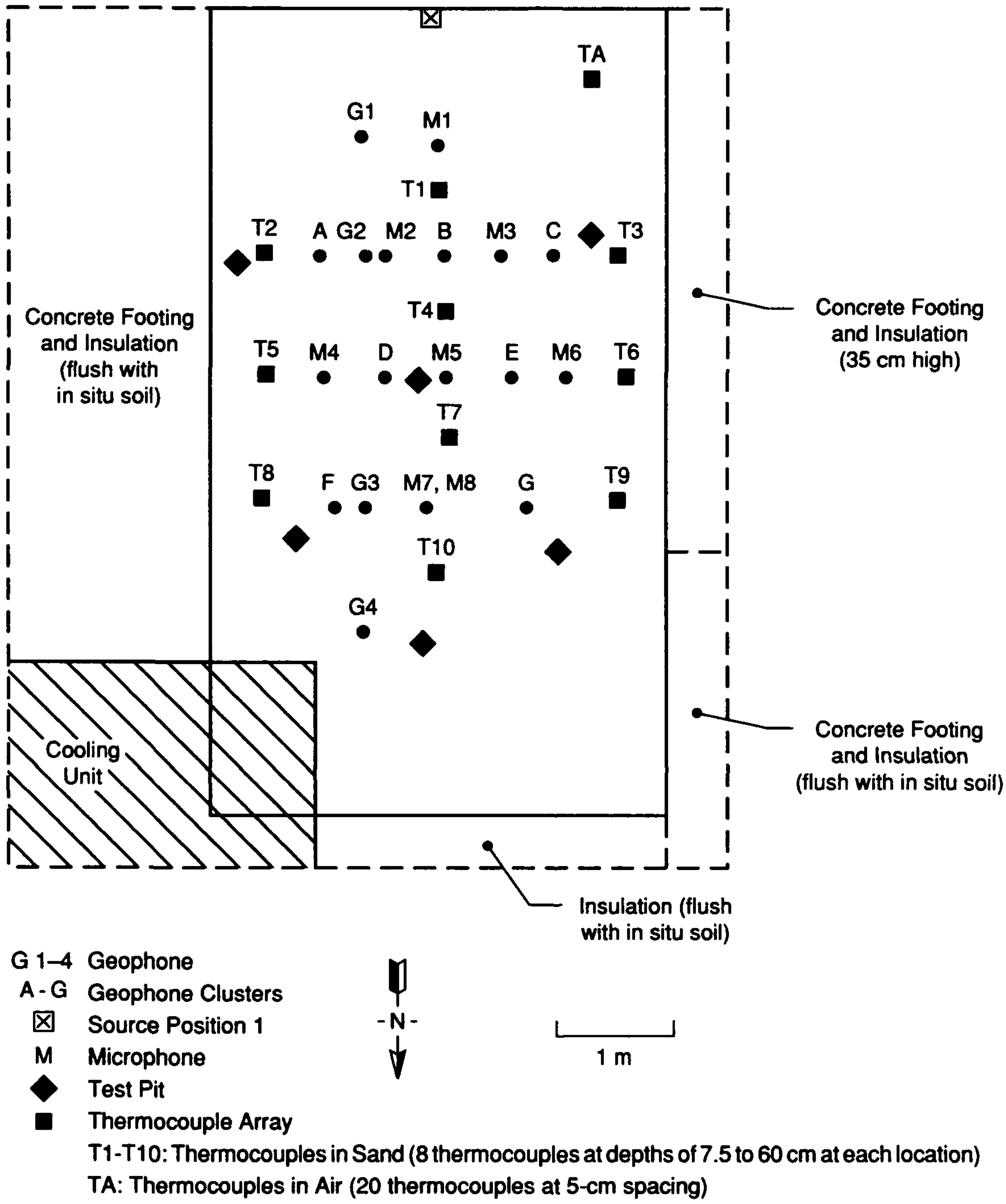


Figure 1. Instrumentation of test basin 1 in the FERF.

The temperature of the sand as a function of depth was measured with 10 vertical arrays (T1–T10, Fig. 1) of copper-constantan thermocouples. Each array had eight thermocouple heads spaced at 7.5-cm intervals between depths of 7.5 and 60 cm. The thermocouples were sampled automatically by a Kaye data logger every 30 minutes and the equivalent temperature was reported to the CRREL central computer.

A single above-ground vertical array of 20 thermocouple heads was located near the southwest corner of the test basin. These thermocouples measured the temperature of the air at 5-cm intervals between 5 and 100 cm heights. This thermocouple array was located on the opposite side of the test basin from the cooling system as a check on how well the fans circulated the cold air in the test basin. When the test basin was open (south wall

and roof removed), the air temperature readings indicated how quickly the cold air inside the basin warmed.

The sand-temperature records and the observations of project personnel indicated that a pocket of cold air would persist along the north wall of the test basin, where the section of permanent roof overhung the sand. No geophones had been placed in this area because it had been anticipated that sound reverberation would be particularly troublesome in this location. An east–west gradient in sand temperature sometimes was present when the contents of the adjacent southeast test basin were being cooled. The cold source along the east wall of the ground-motion test basin supplemented the circulating cold air in cooling the sand.

The acoustic source used in the ground-motion experiments was 0.22-caliber blank fire. The air wave of the pistol fire triggered the seismic system, causing a time-series record of the ensuing ground motion (geophone) and sound pressure level (microphone) to be made. A starter's pistol was fired at a height of 85 cm from one of three locations:

- Along the south boundary of the test basin (Fig. 1),
- 7.2 m to the south, and
- 13.2 m to the south.

For the last two locations the person firing the pistol was standing on the ramp leading from the level of the sand layer to the main floor level of the FERF. Although consistently held at a height of 85 cm above the concrete floor, the incline of the ramp caused the pistol to be 1.6 m above the sand layer when fired at the closest source position on the ramp and 3.5 m above the sand layer when fired at the farthest source position on the ramp.

The two source positions on the ramp were used with the intention of better duplicating a field experiment. At those positions there was greater separation between the source and the sensors and less confinement of the sound by side walls. The amplitude of the acoustically coupled ground motion, however, did not decrease in proportion to the greater propagation distance of the direct sound waves. This was confirmation that the complex geometry of the FERF in the vicinity of the test basin did affect sound levels, and consequently acoustically coupled ground motion, relative to free-field conditions.

The second type of ground-motion source used in the experiments was the contact force due to a sledge hammer striking a steel plate resting on the sand at the source location shown in Figure 1. Next to the plate was a vertical-orientation geophone; the output of that geophone was used solely to trigger the seismic system. Ground motion induced by the hammer blow was measured by the geophone clusters. A complication with this method of activating the recording system was that ground motion induced by vehicle activity outside the FERF also triggered the recording system. This made it particularly difficult on some days to obtain electronically stacked records of ground motion due to hammer blows. Unless the sand was hard frozen, the channels of the recording system corresponding to geophone locations closer than 3 m typically were saturated by the geophones' output voltage. Whether or not the output of the farther geophones saturated the recording system correlated with the local frozen–unfrozen state of the sand. At those locations, the amplitude of ground motion induced by a hammer blow would increase as the sand thawed until it reached saturation level in the unfrozen sand. This was consistent with the changing elastic properties of the sand as it thawed.

TEST CONDITIONS

The acoustically coupled ground motion experiments were done between 26 February and 14 March 1986 (Table 1). The reference test condition was the dry (ambient moisture content), unfrozen sand on 26 February. After that set of experiments, the south wall and roof of the test basin were put in place and the sand was cooled by circulating cold air inside the test basin. By 28 February, the thermocouples in the sand indicated that to a depth of 30 cm the temperature of the sand was below freezing. The test basin was opened up (south wall and roof removed), and a set of ground motion experiments was done. The sand was loose to a depth of approximately 5 cm, but the geophones were more firmly seated in the sand.

The sand was further cooled between 28 February and 3 March, which dropped the temperature of the sand to below freezing to a depth of 53 cm. The loose sand layer at the surface remained; the cohesive sand below it did not collapse when it was unsupported laterally to a depth of 10 cm, but it did crumble when poked. After a set of ground motion experiments on 3 March, the test basin was left open and the sand was warmed by exposure to the air in the FERF. How quickly the sand warmed can be determined from the daily records of the air- and sand-temperature data (Peck 1988). By 5 March, the day of the next experiments, the depth

Table 1. Site conditions.

Date	*Designation*	*Temperature profile of sand*	*Observations*
26 Feb 86	I	Temperature of sand is above freezing (2–3°C) at all depths; varies with depth by 1°C with deeper sand being warmer.	Sand loose.
28 Feb 86	II	Temperature of sand is below freezing to depth of 30 cm.	Sand loose to depth of 5 cm. Geophones more firmly seated.
3 Mar 86	III	Temperature of sand is below freezing to depth of 53 cm.	10-cm-deep pit showed sand loose to depth of 5 cm, cohesive sand below. Cohesive sand did not collapse when unsupported but crumbled when poked.
5 Mar 86	IV	Temperature of sand is below freezing to depth of 53 cm with coldest sand being at 15–38 cm depth.	Sand loose to depth of 5 cm. Cohesive sand below.
7 Mar 86	V	Within accuracy of temperature measurements, sand is unfrozen at all depths.	Sand dry.
	VI	Within accuracy of temperature measurements, sand is unfrozen at all depths.	Sand wetted until water pools on surface. Saturated layer 10–20 cm deep depending on location.
10 Mar 86	VII	Temperature of sand is below freezing to depth of 45–53 cm.	Sand firm to touch except top grains.
12 Mar 86	VIII	Within accuracy of temperature measurements, sand is at frozen–unfrozen transition at all depths, sand at 7.5-cm depth is warmest.	Sand is damp, unfrozen where it had been saturated. Color contrast with unwetted sand.
13 Mar 86	IX	Temperature of sand is within the –1° and –0°C range at all depths.	Sand wetted so it is cohesive. Grains no longer separable. Sand cooled for 3 hr. Sand surface is hard; scattered loose grains. Sand color darkens as it thaws.
14 Mar 86	X	Within accuracy of temperature measurements, sand is at frozen–unfrozen transition at all depths.	Sand loose, damp.
15 Mar 86	—	Within accuracy of temperature measurements, sand is at or above freezing at all depths.	By color and cohesiveness, sand has consistent moisture content from 1 to >55-cm depth.

Note: Because of inherent inaccuracy of temperature determinations with copper-constantan thermocouple cable (±1.5°C by manufacturer's specifications), sand at a given depth is said to be frozen only if the temperature is ≤ –2°C. The temperature of the sand surface is unknown.

to which the sand was below freezing was still 53 cm, but the sand had warmed from the surface down so that the coldest sand was between 15 and 38 cm deep. The sand was still loose to a depth of 5 cm.

The sand continued to warm between 5 and 7 March, when two sets of ground motion experiments were done. The first experiments were of acoustically coupled ground motion in dry, unfrozen sand; unlike the 26 February experiments, the sand had now been through one cooling–warming cycle in the FERF. When this set of experiments was completed, the sand was sprayed with ground water until the water pooled at the surface of the sand layer. Pits dug in the sand (Fig. 1) indicated that the sand was wet to depths of 10 to 20 cm, depending on the location in the test basin. A second set of ground motion experiments was then done. During the 1.75 hours it took to complete this set of experiments, the moisture content of the sand probably was changing to some unknown extent as the water drained into the sand. At the beginning of the test period, however, the moisture content of the upper layer of sand was at or close to saturation.

After the second set of experiments on 7 March, the test basin was closed and the sand was cooled continuously for 3 days. On 10 March the temperature of the sand was below freezing to a depth of 45–53 cm, and the sand was hard frozen. All the geophones were held firmly in the frozen sand. After ground motion experiments on 10 March

were completed, the sand was allowed to warm. By 12 March, the sand was at approximately 0°C at all depths. The sand that had been sprayed on 7 March was noticeable for being damp and for a color contrast with the unwetted sand. The set of experiments done to determine acoustically coupled ground motion on this day was complicated by an inconsistency in the acoustic source. A new supply of 0.22-caliber blanks was being used; of every 6 blanks fired, 1–2 were duds that sounded like handclaps, 2–3 were louder but muffled, and only one had the customary report of blank fire. Since the duds often triggered the recording system, many records had to be discarded. The sand continued to warm overnight, reaching above-zero temperatures to depths of 7.5 to 15 cm. It was evident that the sand would not be completely thawed by 14 March, the last day that the test basin was available for the ground motion experiments.

In an effort to duplicate the test condition of hard frozen sand, on 13 March the sand was sprayed with water and then cooled for almost 4 hours. This did drop the temperature of the sand in the top 7.5 cm to below freezing (–0.5°C) and caused the surface of the sand to be hard frozen; however, the temperature gradient was less than 1°C over 53 cm, with the lowest temperature being –1.4°C. *In contrast, on 10 March the temperature of* the hard frozen sand at a depth of 7.5 cm was –12 to –18°C, depending on location. The final set of experiments was done on 14 March. The sand had warmed overnight and was now damp and loose at the surface. The temperature of the sand was above freezing to a depth of 15 cm; it was less than 1 degree below zero to a depth of 60 cm.

Of the test conditions during the 26 February to 14 March period, three were common field situations: dry, unfrozen sand (26 February, 7 March); saturated sand (7 March) overlying unfrozen sand, as following a rainstorm or snow melt; and hard frozen sand (10 March), as when wet, thawed sand refreezes. On 12 March, when the hard frozen sand had thawed, the sand was damp; in the field this would correspond to the completion of the spring thaw, when there is no longer a subsurface frozen layer to prevent drainage of water released by melting at the surface of the soil.

The cooling–warming cycle with dry sand (28 February–5 March) served to determine the time required to complete such a cycle during winter months when the air inside and outside the FERF is cold; its counterpart in nature would be a location where relatively dry soil passes through freezing and thawing episodes. The existence of the loose top layer (5 cm) of sand is attributed to the lower moisture content of the surface sand, which had been exposed to the drying action of air circulating in the FERF for 10 months without any replenishment of moisture; the dryer sand did not adhere when it was cooled below freezing, whereas the underlying, moister sand became more cohesive. The author has not encountered a similar situation in field experiments because they have been conducted in areas where rain and dew customarily have caused the soil to be moist at the onset of winter. As an example, when a testbed of sand used in acoustic coupling studies at a Maine field site froze, it became a rigid, hard frozen slab similar to the condition of the FERF sand on 10 March; the exception to this was a loose surface layer 2–4 cm thick that would exist for a few hours on warm days when the upper portion of the sand thawed, only to refreeze and become hard later in the day.

PRELIMINARY ASSESSMENT OF ACOUSTICALLY COUPLED GROUND MOTION

The ground motion records for test condition I (26 February) were encouraging in that the first wavelet of ground motion appeared similar in shape to that seen in field experiments. For most vertical geophones, the initial ground motion was a high-amplitude/high-frequency wavelet followed by lower amplitude ground motion in which succeeding peaks were evident. Calculations of travel times for sound reflected from the east, north, and west walls confirmed that the subsequent peaks corresponded to expected arrivals of reflected sound; the arrival times were calculated for a sound speed of 331 m/s, which in the absence of wind (and neglecting humidity and pressure effects) is the speed of sound* in air at 0°C.

An independent determination of the sound speed was made using the travel time of the direct sound wave between pairs of geophones in the linear array. This gave sound speeds of 325, 340, 320, and 230 m/s. The last value was for the shortest propagation distance (0.8 m); it is judged to be

* Note. The equation for the speed of sound in air is

$$C = 20.05\sqrt{T}\left(1 + 0.14\ \frac{E}{P}\right) + U$$

where T is temperature (Kelvin), U is the component of wind speed in the direction of sound propagation, E is the water vapor pressure, and P is the total pressure. Inside the FERF, where there is no wind, temperature is the dominant factor controlling sound speed.

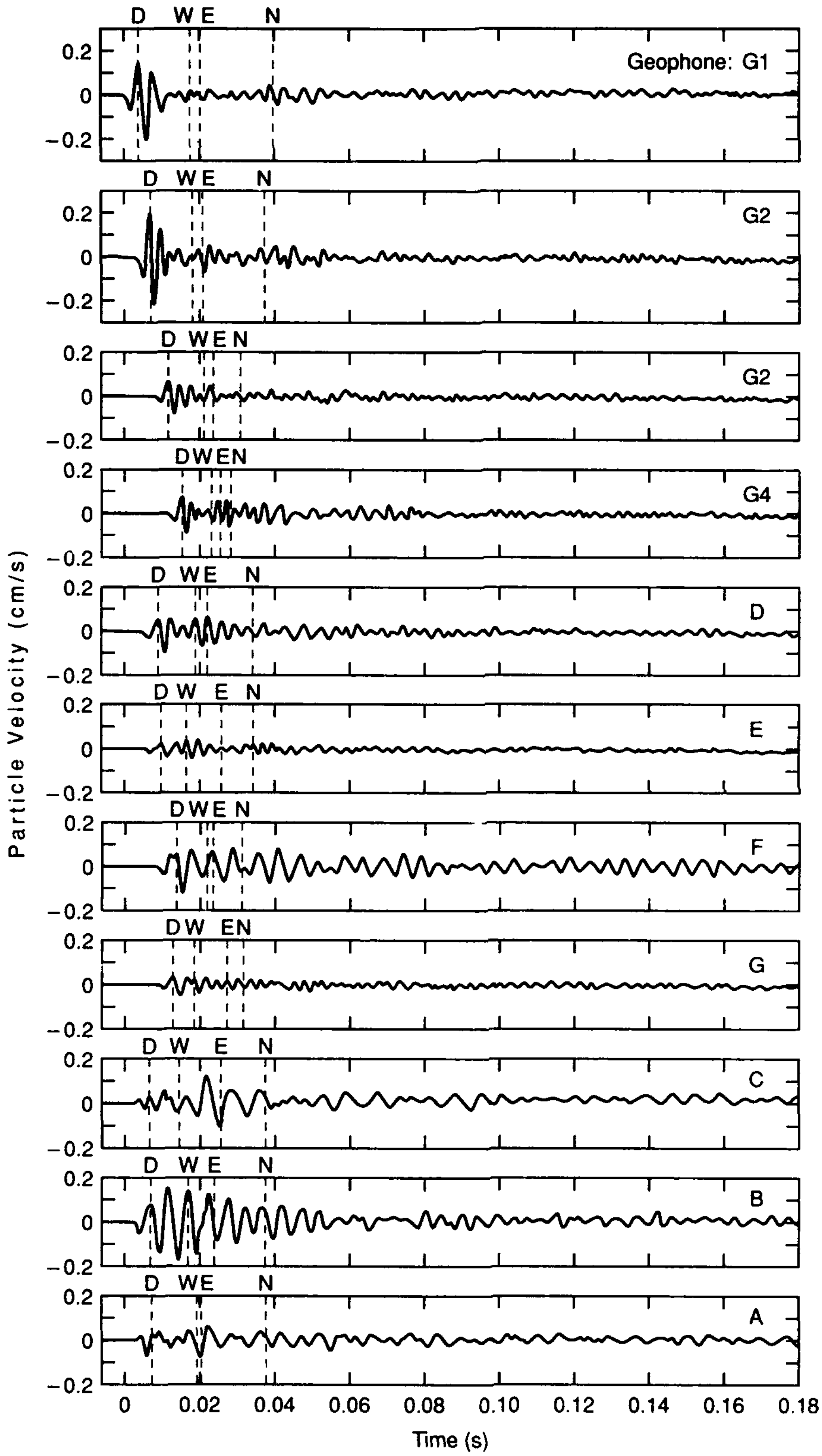


Figure 2. Calculated sound arrivals at the surface geophone of each cluster and at geophones G1–G4 (test condition I). The two horizontal geophones are oriented north–south (A) or east–west (C). D = direct wave; W = west wall reflection, E = east wall reflection; N = north wall reflection.

the least accurate because errors in the measurements of path length and arrival time are much more significant over so short a distance.

Calculated arrivals of reflected sound are shown in Figure 2 for each geophone. The time delay to initiation of ground motion by the passage of the direct air wave increases with distance from the acoustic source. Similarly, sound reflected from the north wall reaches G4 first and more distant geophones successively later. Location in the test basin determines how easily ground motion induced by sound waves reflected at the east and west walls is resolved; at geophones A and F the difference in calculated arrival times is on the order of 1 ms, at geophones E and G it is 9 ms.

Geophone C shows stronger ground motion induced by the sound waves reflected at the east and west walls than that due to the direct or north-wall-reflected sound waves. This is consistent with the geophone being oriented to respond to the east–west component of horizontal ground motion. The sound reflected at the east and west walls passes geophone C along paths with large east–west components. Geophone A, also a horizontal geophone, responds to north–south ground motion. Relative to geophone C, it shows strong ground motion induced by the direct sound wave.

The apparent ground motion at geophone location B was distinctly different from the records of the other vertical geophones. The absence of a high-amplitude/high-frequency initial wavelet of surface ground motion persisted through one cooling–warming cycle until the sand had been wetted (test condition VI). The greater cohesiveness of the moist sand meant that the B surface geophone was more firmly seated in the sand; because of the better coupling between the geophone and the sand, the geophone output more accurately represented the actual ground motion. This interpretation of the apparently anomalous surface motion at location B is consistent with the fact that ground motion at depth at location B did show the initial high-amplitude/high-frequency wavelet. The buried geophones would have been firmly seated in the sand under all test conditions both because of the weight of the overlying sand and because the sand at depth was more cohesive than the dryer, exposed surface sand. Although poor coupling between surface geophone B and the sand during test conditions I through V invalidated those determinations of ground motion at that location, it did serve as an indication of the inaccuracy that may result when a geophone is placed in an infirm medium such as dry, unfrozen sand or powdery snow unless considerable effort is taken to assure good coupling.

A second feature of some geophone records that was present only under certain test conditions was low-amplitude/low-frequency first ground motion. The initial surface ground motion at location D is of low frequency and low amplitude for test conditions II, III, and IV (Fig. 3a). During these experiments there was a shallow layer of loose sand overlying firmer sand. This low-amplitude/low-frequency ground motion was not evident at locations F, G, or G1–G4; it may be present as a much less prominent arrival at location E. (Geophone location B is not considered because the surface geophone was not well coupled to the sand during these experiments, as discussed above.) The low-amplitude/low-frequency initial motion is not evident at the depths of the buried geophones, which are below the loose sand layer. The spottiness of the occurrence of this ground motion within the test basin may be due to local variation in the existence of the shallow sand layer, which would be due to location-dependent differences in the effectiveness of the method of cooling the sand. Another possibility was that the presence of the low-amplitude/low-frequency ground motion was determined by the propagation of a seismic wave initiated by the pistol blast (Albert 1988), particularly if a minimum source–geophone separation was necessary for the seismic wave to be evident at the sand surface, but with slightly farther travel the seismic wave attenuated below detection level.

Given the uncertainty about the nature of the initial low-amplitude/low-frequency ground motion, it is not clear what the occurrence of such ground motion implies with regard to the suitability of the FERF for ground motion studies. If nonuniform freezing of the sand was the reason for the location-dependent occurrence of the low-amplitude/low-frequency ground motion, then that is a liability for future studies. In the field, an area the size of the FERF test basin that was part of a larger open, flat area would be likely to freeze and thaw uniformly, leading to insignificant lateral variation in the frozen–thawed state of the ground, a situation that cannot be duplicated in the FERF with the present method of cooling and warming the sand. If the initial low-amplitude/low-frequency ground motion were due to the passage of seismic waves that existed because of the presence of the shallow layer of loose sand, then closer spacing of the surface geophones would have determined the spatial offset corresponding to its first

appearance and also its attenuation with propagation in the sand; in that case, the FERF would have been shown to be a useful site for ground motion studies under various combinations of unfrozen–frozen layers.

A final consideration in the preliminary assessment of acoustically coupled ground motion in the FERF is the dependence of amplitude upon location in the test basin. Whereas it would be expected that the amplitude of surface ground motion would decrease with distance from the acoustic source, as a consequence of reduced sound pressure levels due to geometrical spreading, Figure 2 shows that the ground motion coupled to the direct sound wave is higher in amplitude at G2 than at G1. A contributing factor to this is any directionality of the source: it is assumed that the sound pressure will be greatest along the axis of the gun barrel. The greater separation between the acoustic source and G2 means that the angle between G2 and the direction of fire is less than the corresponding angle at G1, and presumably the sound incident at G2 originated at a higher pressure level because its direction was closer to the on-axis emission of sound from the gun barrel. To avoid potential source-directionality effects, it would have been necessary either to position all the geophones on a straight line or to locate the acoustic source at a greater distance from the geophones so that all the angles between the line of fire and geophone locations would be small. Using source positions on the ramp to the south of the test basin, however, introduced its own complexity (discussed above) that offset the advantage of the greater source–geophone separations. With regard to having the geophones in a line, they were intentionally placed throughout the test basin in order to determine any dependence of ground motion on location; changes in ground motion arising from the frozen–thawed or dry–saturated state of the sand were unambiguous at each geophone location because the relative position of the pistol barrel was the same for the entire series of experiments and particular source location (adjacent to the test basin or on the ramp).

VARIATION IN ACOUSTICALLY COUPLED GROUND MOTION WITH DIFFERENCES IN SAND CONDITIONS

A time-series record of acoustically induced ground motion at the D geophone cluster is shown for each test condition in Figure 3. The D cluster was selected for this example because the arrivals of reflected sound at its location are well separated. The acoustic source was single 0.22-caliber blank fire at the edge of the test basin. A representative trace is shown for each test condition. Normalized values of peak-to-peak amplitude are given in Table 2. The test conditions considered here are I (dry, unfrozen sand), VI (saturated sand), and VII (hard frozen sand) as these are the particular conditions that were intended to be systematically investigated in the FERF.

Table 2. Normalized amplitudes of D-cluster geophones.

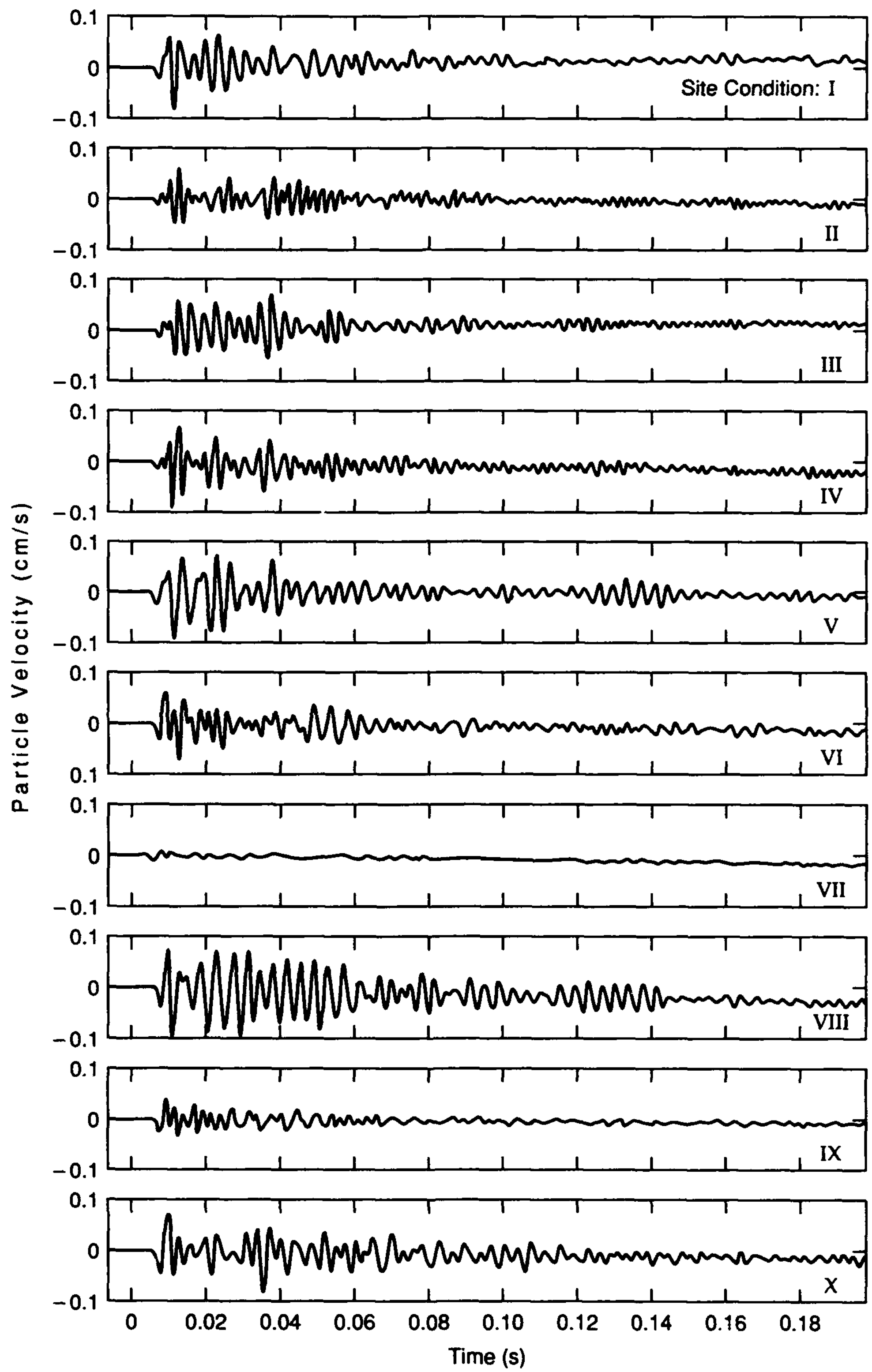
Test	*Surface*		*13 cm*		*20 cm*	
condition	*A*	*B*	*A*	*B*	*A*	*B*
I	1.0	1.0	1.0	1.0	1.0	1.0
II	0.67, 0.66	—	0.88, 0.68	—	0.68, 0.56	—
III	0.50, 0.58	—	0.90, 0.88	—	0.56, 0.55	—
IV	0.97, 0.98	—	0.72, 0.62	—	0.60, 0.51	—
V	1.00, 1.07	1.06, 1.26	1.25, 1.39	1.91, 2.00	1.09, 1.25	1.55, 1.71
VI	0.73, 0.88	1.09, 1.09	0.88, 1.03	1.81, 1.77	0.61, 0.75	1.24, 1.17
VII	0.13, 0.09	0.15, 0.18	0.06, 0.05	0.12, 0.12	0.05, 0.05	0.12, 0.11
VIII	1.27, 1.10	—	0.29, 0.18	—	0.22, 0.15	—
IX	0.43, 0.46	—	0.46, 0.45	—	0.12, 0.10	—
X	0.93, 0.91	—	0.65, 0.55	—	0.63, 0.50	—
Scale factor	—	—	1.60	1.34	1.37	1.20

A and B refer to 2 different sensor combinations.

The two entries under A or B are from repeat experiments approximately 20 minutes apart. B results are presented for only 4 test conditions. The first entry under A in each column corresponds to Figure 3 (a–c).

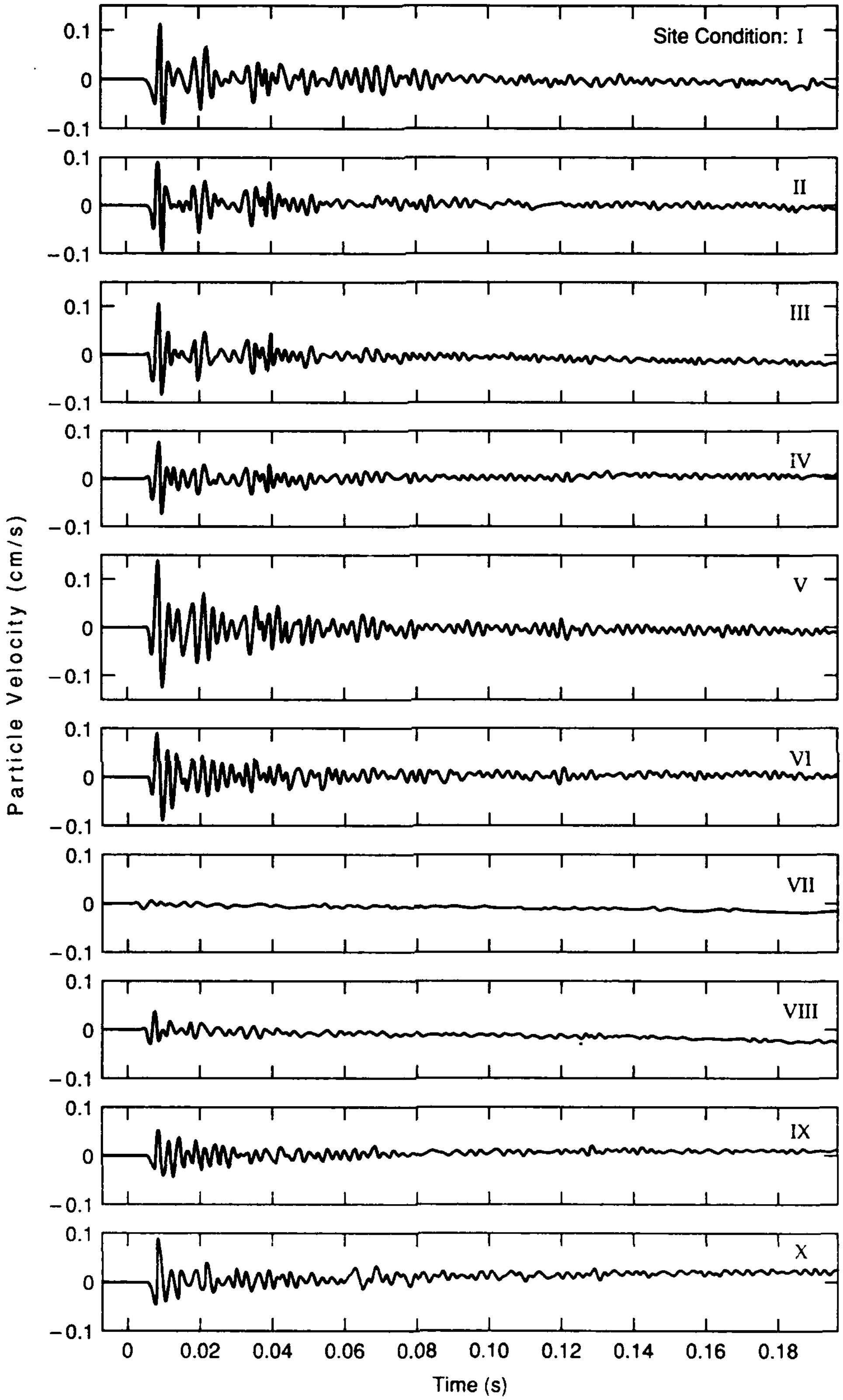
Only one valid record for test condition I was available for either sensor combination.

Scale factor is the number by which the 13-cm and 20-cm entries must be multiplied to be in proportion to the surface entries.



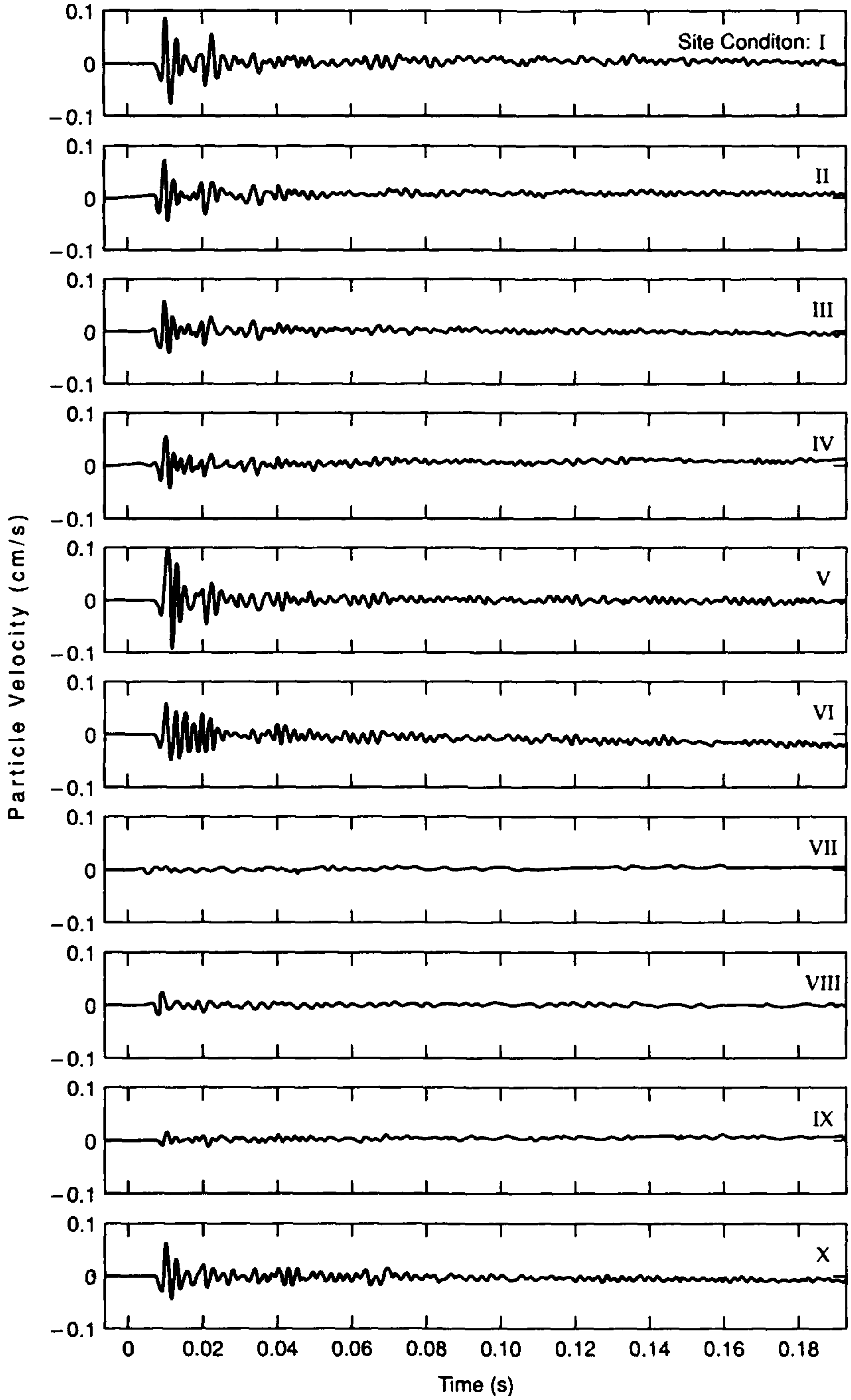
a. At the sand surface.

Figure 3. Time series records of the D-cluster geophones. The acoustic source was a 0.22-caliber blank fired at a range of 3 m. One trace is shown for each site condition.



b. At a depth of 13 cm.

Figure 3 (cont'd).



c. At a depth of 20 cm.

Figure 3 (cont'd). Time series records of the D-cluster geophones. The acoustic source was a 0.22-caliber blank fired at a range of 3 m. One trace is shown for each site condition.

At the sand surface (Fig. 3a) the direct-wave ground motion was of higher frequency in the saturated sand (VI), suggesting that coupling between the geophone and sand had improved. Acoustically coupled ground motion in hard frozen sand (VII) was greatly reduced in amplitude.

At depths of 13 cm (Fig. 3b) and 20 cm (Fig. 3c), the direct-wave motion in dry, unfrozen sand was well defined, with a higher frequency than at the surface. This is consistent with better coupling between the geophone and the sand when the geophone is buried. The occurrence of ground motion induced by reflected sound is seen clearly at both depths. The amplitude of the first wavelet of ground motion was smaller in the saturated sand than in either the initial dry, unfrozen sand (I) or the dry sand that had been through a cooling–warming cycle (V). At both depths the acoustically coupled ground motion in the hard frozen sand (VII) was reduced by 80–90% relative to that in dry, unfrozen sand (I).

A comparison of the three sets of traces indicates several depth-dependent aspects of the coupled ground motion. First, the peak-to-peak first motion at the 20-cm depth was always less than that at the 13-cm depth. This is consistent with the attenuation of the sound wave as it propagated through the sand layer. Second, the recovery from the hard frozen state was delayed with depth. The first test series after the hard frozen sand had begun to thaw (VIII) showed that the surface motion was the same as for unfrozen sand, the amplitude of the motion at the 13-cm depth was 30% of that in condition I sand, and the amplitude of motion at the 20-cm depth was 20% of that in the condition I sand.

The lower amplitude of the coupled ground motion at depth in saturated sand is consistent with reduced air permeability due to increased moisture content of the sand (Prout 1961, Aljibury and Evans 1965, Cramond and Don 1987). The reduction in amplitude was ~30% at the 13-cm depth and ~40% at the 20-cm depth, relative to ground motion in condition I sand.

Upon freezing the saturated sand, the water in the pore spaces became ice that firmly bonded the sand grains. One consequence of this was that the compressional wave speed in the sand layer, as determined with hammer blows, was higher due to the different compressional wave speeds in water (~1500 m/s) and ice (~3000 m/s). Similar changes in compressional wave speed in earth materials have been reviewed by Scott et al. (1990). The change in elastic properties upon freezing the saturated sand was evident also as lower amplitude ground motion in response to a hammer blow. Ground motion at surface geophone D due to a hammer blow saturated the recording system under all test conditions except the hard frozen sand, when the amplitude of the ground motion was 42% of the saturation value. The higher stiffness of the ice-bonded sand meant that the same contact force would cause a smaller displacement of the sand.

The variation in acoustically coupled ground motion with whether the sand was dry, saturated, unfrozen, or frozen (Fig. 3, Table 2) confirms that these variables should be systematically investigated. The FERF experiments, particularly the contrast between dry unfrozen sand and hard frozen sand, were extreme conditions. The limitation on resolving the effects of moisture content or frozen–unfrozen state of the sand would be the reproducibility of the measurements of ground motion. Table 2 shows that there generally is good agreement between repeat experiments when the only variable is the test condition. When a change in the set-up of the recording system is also made (compare set A and set B entries for test condition V), then the variation in ground motion due to the different test conditions is less certain.

CONCLUSIONS

The use of a test basin in the FERF for experiments in acoustically coupled ground motion has helped to determine the variation in coupled ground motion when the sand is saturated or wet sand is frozen. These extreme cases caused a depth-dependent reduction in ground-motion amplitude of 30–40% (wet vs dry sand) and 80–90% (hard frozen vs unfrozen sand). The differences in ground motion induced by blank pistol fire due to changes in the frozen–thawed and dry–saturated state of the sand could be distinguished from background seismic noise caused by machinery operating in the FERF or vehicles outside the building.

This series of experiments demonstrated an effective, unconventional means of cooling the contents of a test basin, but showed that the method of warming the test basin, which was to expose it to the air in the FERF, is inadequate due to its slowness during winter months. An improvement in controlling the freezing of the sand would be to have feedback between the thermocouples in the sand and the fans circulating the frigid air such that the fans would be automatically shut off when the temperature of the sand at a particular depth

dropped below freezing. If the ground motion experiments are then done within a day or so, the sand is unlikely to warm significantly as long as the test basin remains closed. Being able to control the depth of the freezing front would permit systematic investigation of the changes in coupled ground motion as the frozen layer thickens.

A method of drying the sand would make it possible to vary the moisture content of the sand in a controlled manner and thus determine its influence on acoustically coupled ground motion.

LITERATURE CITED

Albert, D.G. (1988) Preliminary analysis of acoustic-to-seismic coupling experiments at Grayling, Michigan. USA Cold Regions Research and Engineering Laboratory, Internal Report 1027 (unpublished). (Abstract and figures of paper presented at the 17th meeting of NATO-RSG 11, France.)

Aljibury, F. K. and D.D. Evans (1965) Water permeability of saturated soils as related to air permeability at different moisture tensions. *Soil Science*, **29**: 366–369.

Cramond, A. J. and C.G. Don (1987) Effects of moisture content on soil impedance. *Journal of the Acoustical Society of America*, **82**: 293–301.

Peck, L. (1988) Freeze/thaw cycling of a sandbed in the FERF. USA Cold Regions Research and Engineering Laboratory, Internal Report 998 (unpublished).

Prout, J.H. (1961) Some measurements of the absorption coefficient of soil, using the impedance tube technique. *Noise Control*, **1**: 20–23.

Scott, W.J., P.V. Sellmann and J.A. Hunter (1990) Geophysics in the study of permafrost. In *Geotechnical and Environmental Geophysics, Vol. 1, Review and Tutorial* (S.H. Ward, Ed.). Tulsa, Oklahoma: Society of Exploration Geophysicists, p. 355–384.

APPENDIX A: TEST BASIN 1 SPECIFICATIONS

Test basin 1 is a 7.6-m × 6.4-m cell in the most southwest corner of the test area of the FERF. It is bounded on the west by a concrete wall in common with the mobilization aisle, on the north by a plank wall in common with test basin 2, on the east by a concrete wall in common with test basin 8, and on the south by a removable wooden wall constructed for this project.

The basin was covered with two sections of insulated, wooden roof. The northernmost section of the roof was fixed in place. It supported the cooling system, provided access to the test basin through a trap door, and when in place served as a walkway spanning test basin 1. Most of the basin was covered with a removable roof. This roof section rested on top of the concrete wall in common with test basin 8 and on an angle iron running the length of the west wall. At both the east and the west ends two eyebolts were placed symmetrically about the east–west centerline of this roof section. Short chain lengths connected the eyebolts. The roof was raised and lowered using the block-and-hoist assemblies attached to a rolling gantry that spanned the width of the FERF test area. Once the roof was free-hanging, i.e., raised above its side supports, it could be moved by two people pushing the gantry on its tracks. When not in place, the roof was set down to the north of test basin 1.

The south wall was raised and lowered using one block–and–hoist assembly attached to the gantry. It pivoted on its base with little lateral translation. A person standing on the roof could attach the block–and–hoist assembly to eyebolts in the top of the wall. The wall was lowered prior to moving the roof. It rested on the ramp adjacent to test basin 1 when not in use. The movable wall was slightly less than the width of the test basin; narrow floor-to-roof stationary sections served as stops for the wall.

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A series of ground-motion experiments was done in the Frost Effects Research Facility at CRREL in 1985 and 1986 to determine the suitability of the FERF for studies of ground motion induced by low-frequency acoustic sources. A special method of freezing the contents of a FERF test basin by circulating frigid air was effective in freezing sand to a depth of 53 cm. The reverse means of thawing the sand, exposing it to the ambient temperature air in the FERF, did not allow for expeditious warming of the sand during winter months. Acoustically coupled ground motion was measured for sand conditions of dry, unfrozen; dry, frozen; saturated; and hard frozen. Ground-motion amplitude was 30–40% lower in saturated sand than in dry, unfrozen sand. This depth-dependent reduction is attributed to reduced air permeability in the saturated sand. The amplitude of acoustically coupled ground motion in hard frozen sand (sand frozen when wet) was 80–90% lower than in dry, unfrozen sand.

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